AD-769 885

PHYSICAL PROPERTIES AND THE MECHANICS OF PENETRATION AND LOADING OF BULK MATERIALS AS RELATED TO RAPID EXCAVATION

Kelvin K. Wu, et al

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The report describes work performed

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The objective was to obtain information on the physical properties of fragmented mined materials from both conventional and mechanical boring rapid excavation methods and to investigate the mechanics of penetration and loading of these materials. This infromation was used to determine the effects of physical properties of materials fragmented during the rapid excavation process on the equipment response. A total of 52 samples from 23 mining and tunnel sites were tested. Holmes & Narver, Inc., of Anaheim, Calif., was furnished physical

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20. Abstract (Continued)

property data from this project for their use in an ARPA-sponsored research contract (contract H0220023 "Study of Interrelationship of In Situ Rock Properties, Excavation Methods, and Muck Characteristics") monitored by the Pittsburgh Mining and Safety Research Center. The results of this research are available in a report (AD-764 977).

Linear penetration tests were run using mainly confined materials. The tests were performed with bulk materials in loose and compacted states. Analysis of variance was applied in order to identify the most important variables and co-variables which affect the penetration process. This task has been accomplished by choosing representative bulk materials for the tests. For each bulk material used for the analysis, a petrographic thin-section was prepared and examined for the purpose of determining the major minerals in this particular sample. The results of the analysis of variance of the penetration tests showed that the type of material and the state of compaction were highly significant factors in the work required for a digging tool to penetrate a pile. The wedge angle was only slightly significant. The analysis also showed that the material size-compaction interaction was highly significant in the data, but the wedge angle-compaction and wedge angle-material size were not as significant.

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ANNUAL TECHNICAL REPORT SUMMARY

Objective:

To obtain basic and practical information on the physical properties of fragmented mined materials obtained from both conventional and mechanical boring rapid excavation methods and to investigate the mechanics of penetration and loading of these materials. This information will be used to determine the effects of physical properties of materials fragmented during the rapid excavation process on the equipment response.

Research Plan:

Muck sample acquisition and basic physical properties measurements are continuing efforts. During this second year, emphasis has been on collecting and testing samples of hard rock. An experimental testing program on penetration and loading constituted the major portion of the work schedule. Statistical analysis was employed in this phase of the work in order to determine the significance of individual properties.

Major Accomplishments:

Through the efforts of Holmes & Narver, Inc., 52 samples from 23 mining and tunnel sites have been obtained. The laboratory physical properties testing program for all the muck samples was carried out and completed at Pittsburgh Mining and Safety Research Center. Results of the property tests are shown in Table 1. This data was also sent to Holmes & Narver for their use in fulfilling the terms of a contract with PMSRC on rapid excavation.

Linear penetration tests were run using mainly confined materials. The tests were performed with bulk materials in loose and compacted states. Analysis of variance was applied in order to identify the most important variables and co-variables which affect the penetration process. This task has been accomplished by choosing representative bulk materials for the tests. For each bulk material used for the analysis, a petrographic thin-section was prepared and examined for the purpose of determining the major minerals in this particular sample.

The laboratory digging and loading apparatus, an improved abrasion tester, a large triaxial shear testing apparatus, and a slot-bin hopper were completed during the first half of this fiscal year. Unfortunately, due to a severe reduction in personnel and termination of the funding, this equipment will not be used as had been planned.

The results of the analysis of variance of the penetration tests showed that the type of material and the state of compaction were highly significant factors in the work required for a digging tool to penetrate a pile. The wedge angle was only slightly significant. The analysis also showed that the material size-compaction interaction was highly significant in the data, but the wedge angle-compaction and wedge angle-material size were not as significant.

TABLE 1. - Basic Physical Properties of Mined Material

Sample	Moisture content, percent	Specific gravity	Atterberg limits						Potential volume change	Angle of repose Height of drop, degree		Angle of slide, degree	Angle of internal friction, degree
			Liquid limit, percent	Plastic limit, percent	Shrinkage limit, percent	Plasticity index, percent	Flow index	Toughness index		1"	10"		
SF-1	13-17	2.86	17.75	16.19	13.94	1.56	5.8	0.27	0	38	33	36	42
WP-1	5-7	2.73	16.90	15.50	15.18	1.40	5.0	0.28	0	35	29	28	29
NAST-1	8-10	2.69	14.50	14.00	13.50	0.5	3.0	0.16	0	37	36	41	42
LAW-3	6-7	2.80	11.80	10.6	10.0	1.2	2.9	0.41	0	41	40	38	32
LAW-2	12-13	2.83	12.50	12.3	9.6	0.2	4.0	0.05	0	39	38	31	30
H-2	2-3	2.70	18.0	17.0	13.4	1.0	4.4	0.23	0	40	37	32	44
SF-2	13-15	3.02	31.5	26.8	21.5	4.7	7.6	0.61	0	38	36	30	27
LAW-4	7-9	2.73	20.2	20.0	13.5	0.2	4.7	0.05	0	42	34	37	28
MB-1	5-7	4.34	17.8	15.1	13.9	2.7	4.1	0.66	0	37	35	31	35
PHIL	7-10	2.57	24.0	23.3	22.7	0.7	4.0	0.17	0	39	37	40	30
WP-2	2-3	2.63	23.0	17.63	17.58	5.37	6.9	0.78	0	32	31	29	44
LAY-1	3-4	2.66	21.2	17.06	15.17	3.14	6.0	0.52	0	37	35	27	38
NAST-3	2-4	2.65	19.5	17.41	17.13	2.09	4.1	0.51	0	39	36	31	38
MIL-1	2-4	2.89	16.9	15.69	15.46	1.21	5.0	0.24	0	36	35	30	35
GA-1	1	2.59	16.2	15.78	13.67	0.42	3.0	0.14	0	39	36	34	46
LK-1	0.9	2.85	18.1	17.98	17.69	0.12	3.9	0.3	0	33	30	29	43
LK-2	3-5	2.73	20.50	19.14	17.29	0.36	6.2	0.058	0	43	42	33	39
LK-3	1-2	3.21	18.25	17.92	17.80	0.33	5.5	0.06	0	30	29	29	41
H-2	3-4	2.60	18.10	17.95	11.0	0.15	3.2	0.04	0	38	35	38	44
WNG-1	10-11	2.71	24.90	19.97	19.94	4.93	7.4	0.66	0	34	31	32	27
WNG-2	0.9	2.72	25.25	24.74	23.37	0.51	4.0	0.13	0	32	31	40	28
NAV-1	7-8	3.13	36.80	23.61	21.04	13.19	7.0	1.88	1.3	30	30	30	36
NAV-2	8-9	2.72	18.20	16.91	16.60	1.29	4.5	0.28	0	31	28	32	28
NAST-4	6-8	2.64	19.20	18.97	17.50	0.23	3.4	0.06	0	39	34	40	33
MIL-2	5-6	2.93	20.10	16.68	16.37	3.42	6.1	0.56	0	32	30	30	33
LK-4	1-2	3.36	19.0	17.95	16.43	1.05	5.4	0.19	0	37	35	30	43
LK-5	3-4	2.67	25.0	20.95	19.68	4.05	5.5	0.73	0	33	32	38	37
11-3	1	2.65	15.6	14.81	14.51	0.79	3.0	0.26	0	25	25	29	46
KM-1	11-13	2.87	28.3	24.97	19.12	3.33	3.6	0.92	0	29	28	31	35
11-4	1	2.78	15.80	15.60	13.26	0.2	4.0	0.05	0	28	29	28	54
LK-6	2-4	2.53	19.40	18.16	17.27	1.24	4.0	0.31	0	30	29	32	40
LK-7	1-2	2.68	18.0	17.12	17.04	0.88	5.0	0.18	0	29	26	28	45
MIL-3	2-3	2.78	15.2	14.40	12.96	0.80	3.5	0.22	0	36	32	32	36
SM-1	1	2.72	12.5	11.02	10.52	1.48	5.1	0.29	0	36	31	28	44
MSG-1	1	2.74	13.80	12.77	10.78	1.03	3.2	0.32	0	35	29	27	46
HS-1	2-3	2.84	18.8	16.06	15.12	2.74	2.7	1.01	0	40	34	31	39
LAY-2	3-4	2.68	15.0	14.18	13.8	0.82	4.0	0.21	0	38	32	32	39
WI-1	2-3	2.81	15.1	13.69	11.57	1.41	3.0	0.47	0	37	31	31	42
72-1	1-2	2.72	18.0	17.1	15.58	0.9	4.4	0.2	0	38	32	30	41

INTRODUCTION

In the mining industry, the rate of loading and conveying of mined material from the working area all the way to a storage or shipping area is a factor which affects the rate of advance of excavation and can be a bottleneck. This is especially true as the rate of advance in hard rock using conventional fragmentation methods increases significantly.

The principle objective of the research at the Pittsburgh Mining and Safety Research Center for materials handling is to find out what factors influence the penetration and loading processes and what effects the physical properties of the mined materials have on these processes. Through these research efforts, it may be possible to obtain better means for selecting handling equipment and an efficient method of removing mined materials.

The force a machine is capable of applying to the digging teeth and the response of the material to the penetrating tools (if penetration occurs) will determine whether or not the machine is capable of excavating a given material. Examination of the digging tools of diverse mining equipment, coal ploughs, backhoes, scrapers, bucket ladder dredges, certain types of drills and so forth, shows that many have in common wedge-shaped digging teeth or edges.

One is thus led to an examination of wedge penetration processes in geologic materials as a rational basis for selecting certain types of mining equipment.

DATA ANALYSIS

When this program was initiated, it was intended that the physical properties of the bulk samples be correlated with such tests as the linear penetration experiments to give expressions helpful in delineating the digging properties of granular materials. Linear penetration tests were completed for 52 field samples for 13 wedge type and angle combinations, and two levels of sample packing: loose and compacted. The wedge and angle combinations were: Circular wedge with face angles of 20°, 30°, and 45°; full wedge with face angles of 20°, 30°, and 45°; half-wedges with face angles of 20°, 30°, and 45°; conical wedges with face angles of 15°, 20°, 30°, and 45°. In the experiments, the wedge was driven into the granular bulk samples a depth of 6 inches. The speed was held constant at 0.05 in/sec. The force and the time integral of the force signal were applied to the input terminals of an XYY' plotter. Figure 8 is a typical record of one experimental run. The X axis depicts the penetration depth, the lower curve shows the force required, and the upper curve shows the time integral of the force signal. The integrated signal is proportional to work since the wedge entry is at constant velocity and the electronic integrator has time as the independent variable. In the analysis it was decided to select four representative samples from the large data set and examine the data in some depth before proceeding to a total analysis. The samples selected were identified as LK-1, LK-2, NAST-3, and KM-1. These samples are described as follows:

1. LK-1 (Fig. 1 and 2)

An igneous rock, biotitic quartz monzonite.

Approximate composition:

25 percent quartz
55 percent Silicic Feldspars
20 percent accessory minerals (Augite, Hornblende, Biotite, Apatite)

Silicic Feldspars:

40 percent Orthoclase → 22 percent of total
60 percent Plagioclase → 33 percent of total

Hardness - Schmidt 53
High strength

2. LK-2 (Fig. 3 and 4)

An igneous rock, biotitic quartz monzonite.

Approximate composition:

22 percent quartz
58 percent Silicic Feldspars
20 percent accessory minerals (Augite, Hornblende, Biotite, Apatite)

Silicic Feldspars:

40 percent Orthoclase → 23 percent of total
60 percent Plagioclase → 35 percent of total

Hardness: Schmidt 56
High strength

3. NAST-3 (Fig. 5 and 6)

An igneous rock, biotitic granite.

Approximate composition:

20 percent quartz
75 percent Silicic Feldspars
5 percent accessory minerals (Augite, Hornblende, Biotite, Muscovite)

Best Available Copy for all Pictures

FIGURE 1. - Photomicrographs of LK-1.

FIGURE 2. - Photomicrographs of LK-1.

FIGURE 3. - Photomicrographs of LK-2.

FIGURE 4. - Photomicrographs of LK-2.

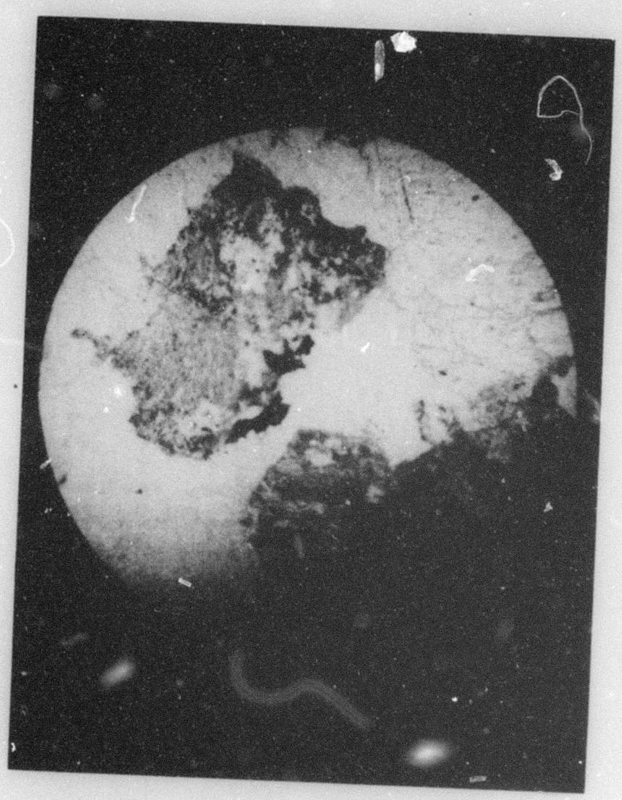


FIGURE 5. - Photomicrographs of NAST-3.

FIGURE 6. - Photomicrographs of NAST-3.

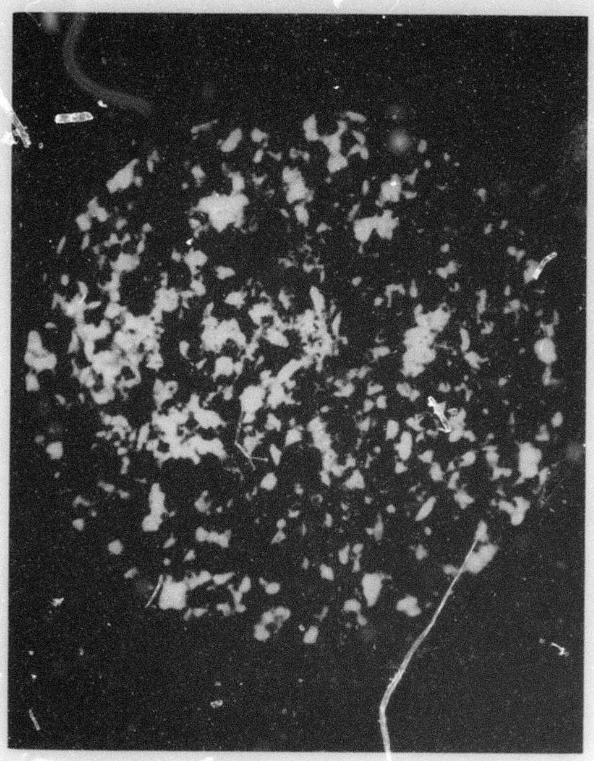


FIGURE 7. - Photomicrographs of KM-1.

Silicic Feldspars:

50 percent Orthoclase → 38 percent of total
30 percent Microcline → 22 percent of total
20 percent Plagioclase → 15 percent of total

Hardness: Schmidt 54
High strength

4. KM-1 (Fig. 7)

A sedimentary rock. Siltstone.

Approximate composition:

60 percent carbonaceous materials
20 percent quartz
15 percent Feldspars
5 percent Micas

Hardness: Schmidt 42
Medium strength

In figures 8 through 15 are shown typical penetration test output curves for these four samples. As a first step, a regression analysis was performed on the work versus penetration data to provide parameters for correlating the physical properties with the penetration test results. Since the output data existed in the form of xy plots, it was necessary to digitize these plots to obtain data pairs which could be submitted to a standard computer regression routine. Accordingly, each of the plots for each sample, each wedge and angle combination, and the two states of sample compaction were digitized with an electronic device which recorded the data pairs on punched paper tape. The tape thus contained the work required to penetrate to depths of 6.0 inches by 0.6 inch increments (10 data points). These tapes were then employed as input to a standard computer regression routine for the form $y = AX^B$.

This routine determined the value of the coefficients A and B, and provided a measure of the "goodness of fit" of the resulting regression curve. Plots were also made of the original digitized data with the regression curve superimposed. A typical plot of these results is shown in figure 16, for sample LK-1. Tables 2 through 9 contain the results of the regression analysis for each of the four representative samples. Also contained in these tables is a value for the total work required for a penetration depth of 6 inches as calculated from the regression curve.

This value, the work required to penetrate 6 inches, was used in the next step of the analysis to determine which parameters had a significant effect on the work of penetration into the granular samples. The calculated values of work required to penetrate at depths of 6 inches are also displayed in table 10, in the classical format for an analysis of variance. The analysis was performed and the results are displayed in table 11.

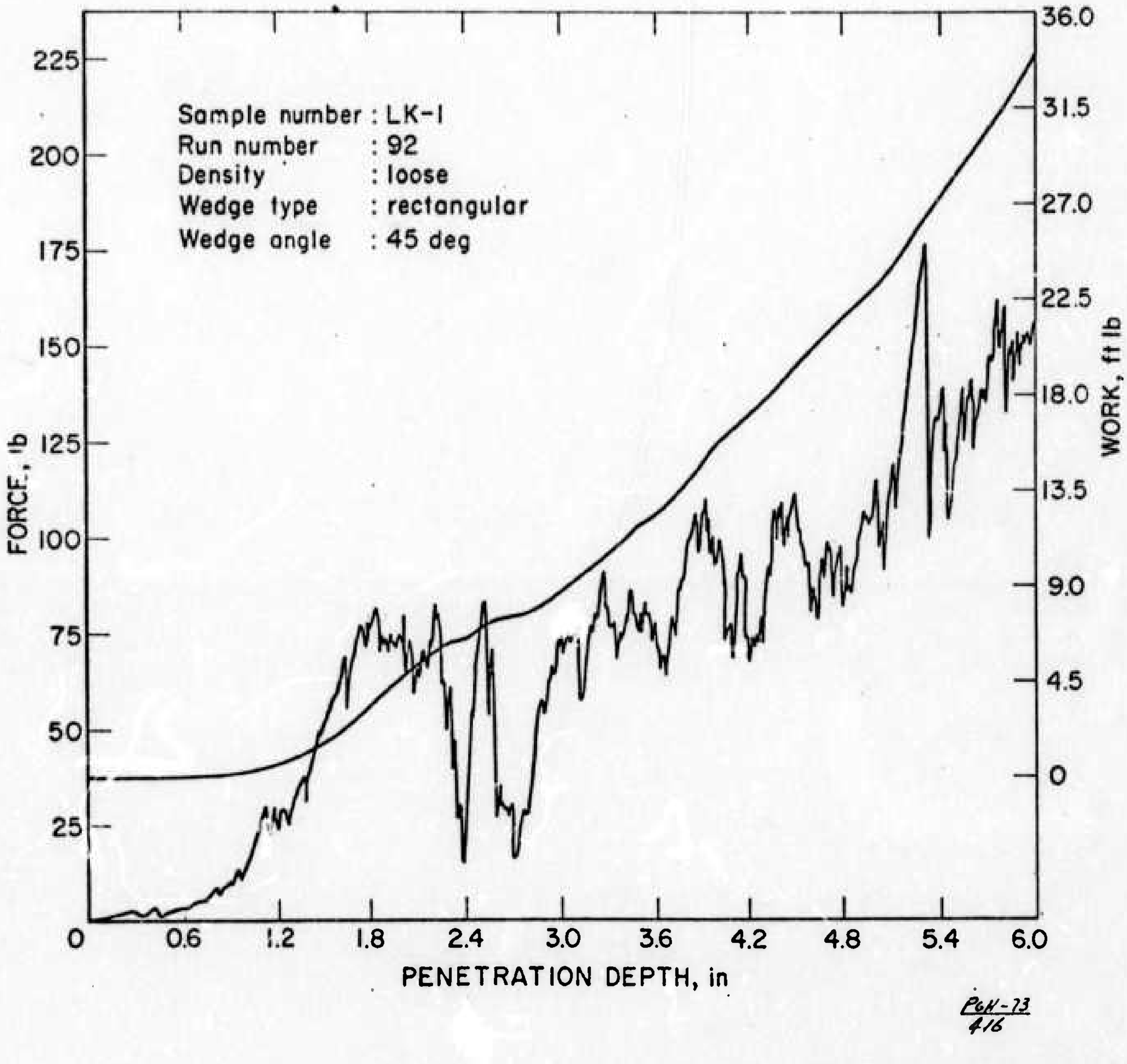


FIGURE 8. - Penetration Test Experimental Data of LK-1.

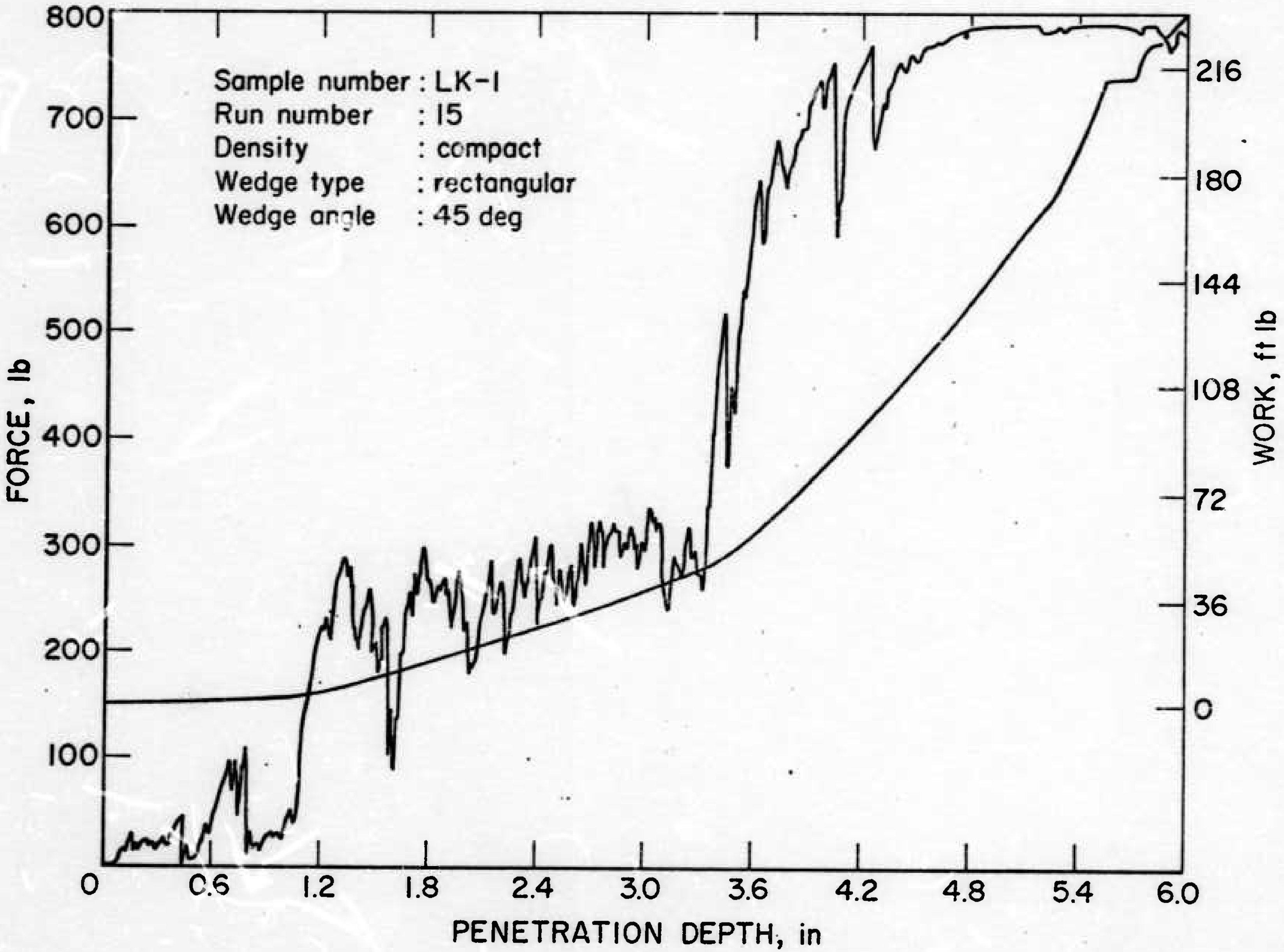
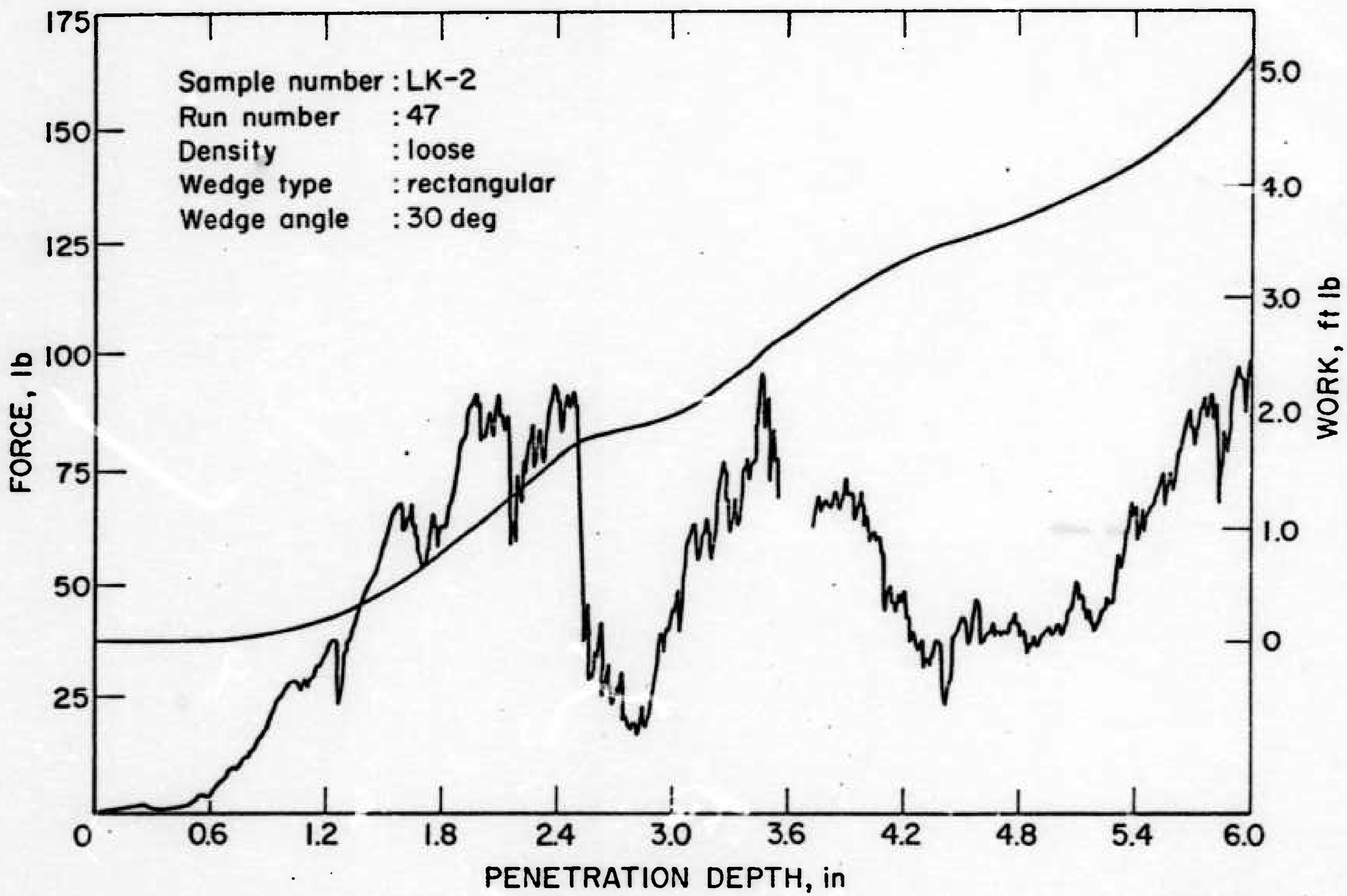


FIGURE 9. - Penetration Test Experimental Data of LK-1.

PGH-73
415



PGH-73
418

FIGURE 10. - Penetration Test Experimental Data of LK-2.

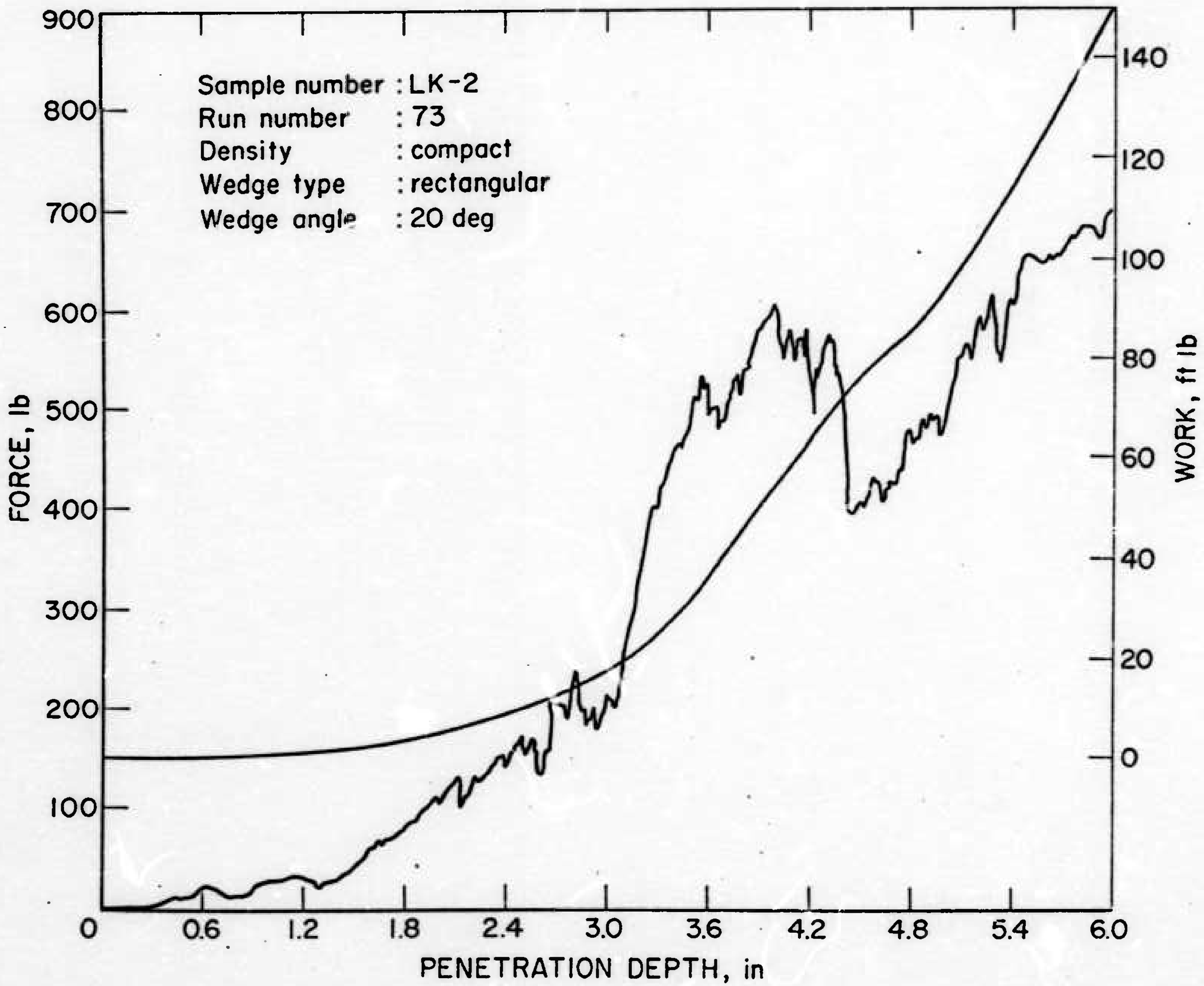
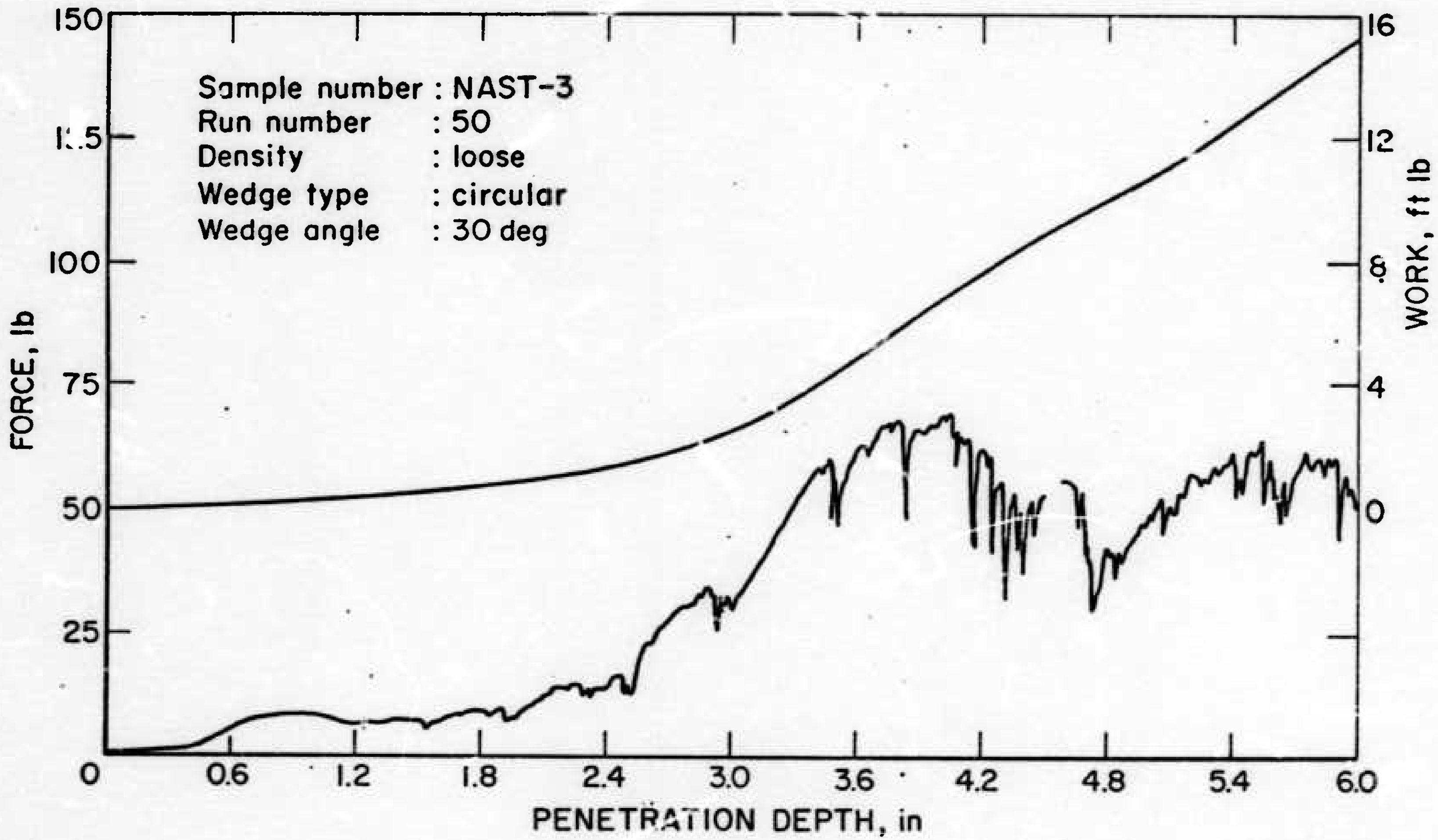


FIGURE 11. - Penetration Test Experimental Data of LK-2

PGH-73
4'7



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419

FIGURE 12. - Penetration Test Experimental Data of NAST-3.

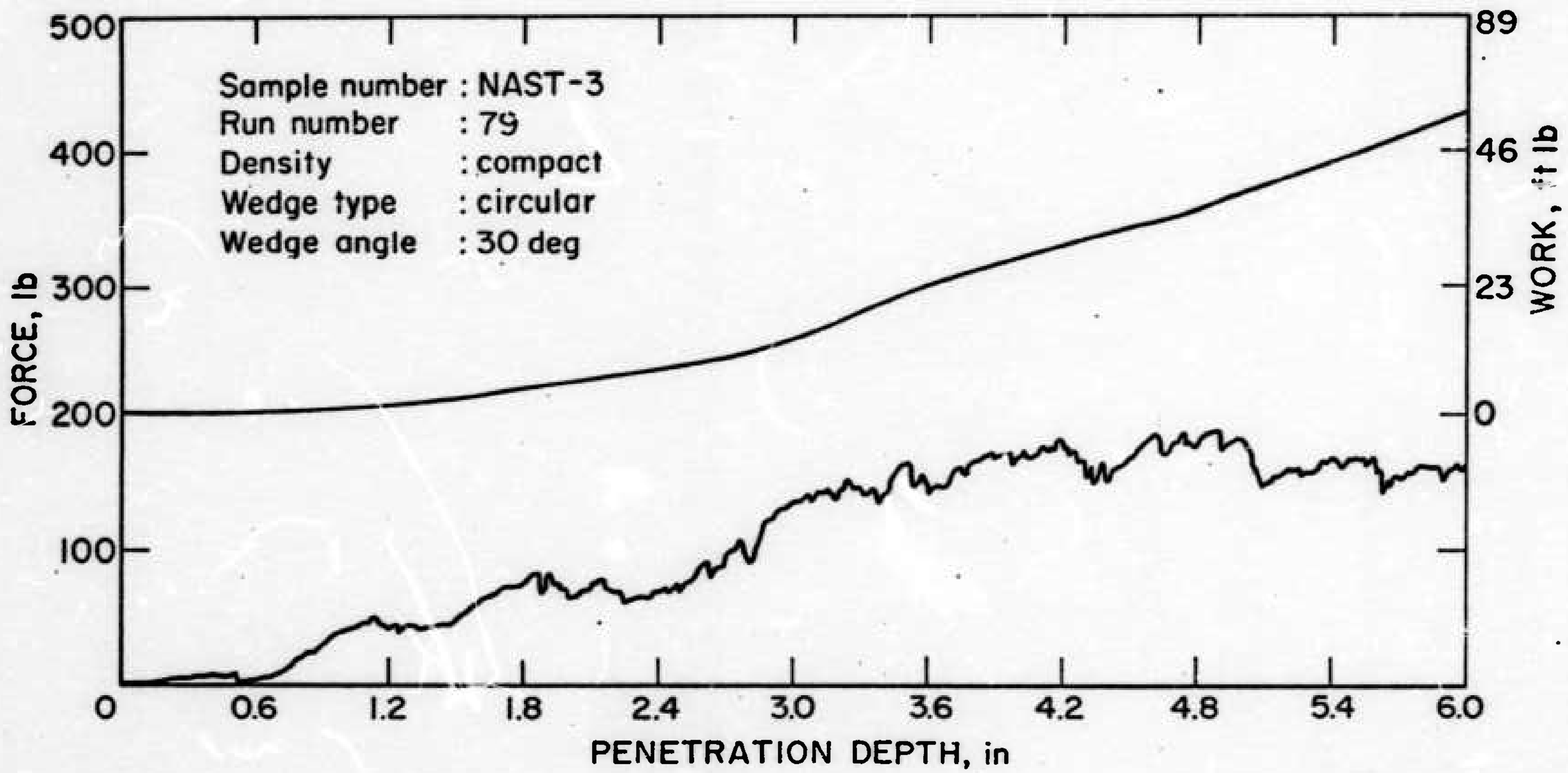

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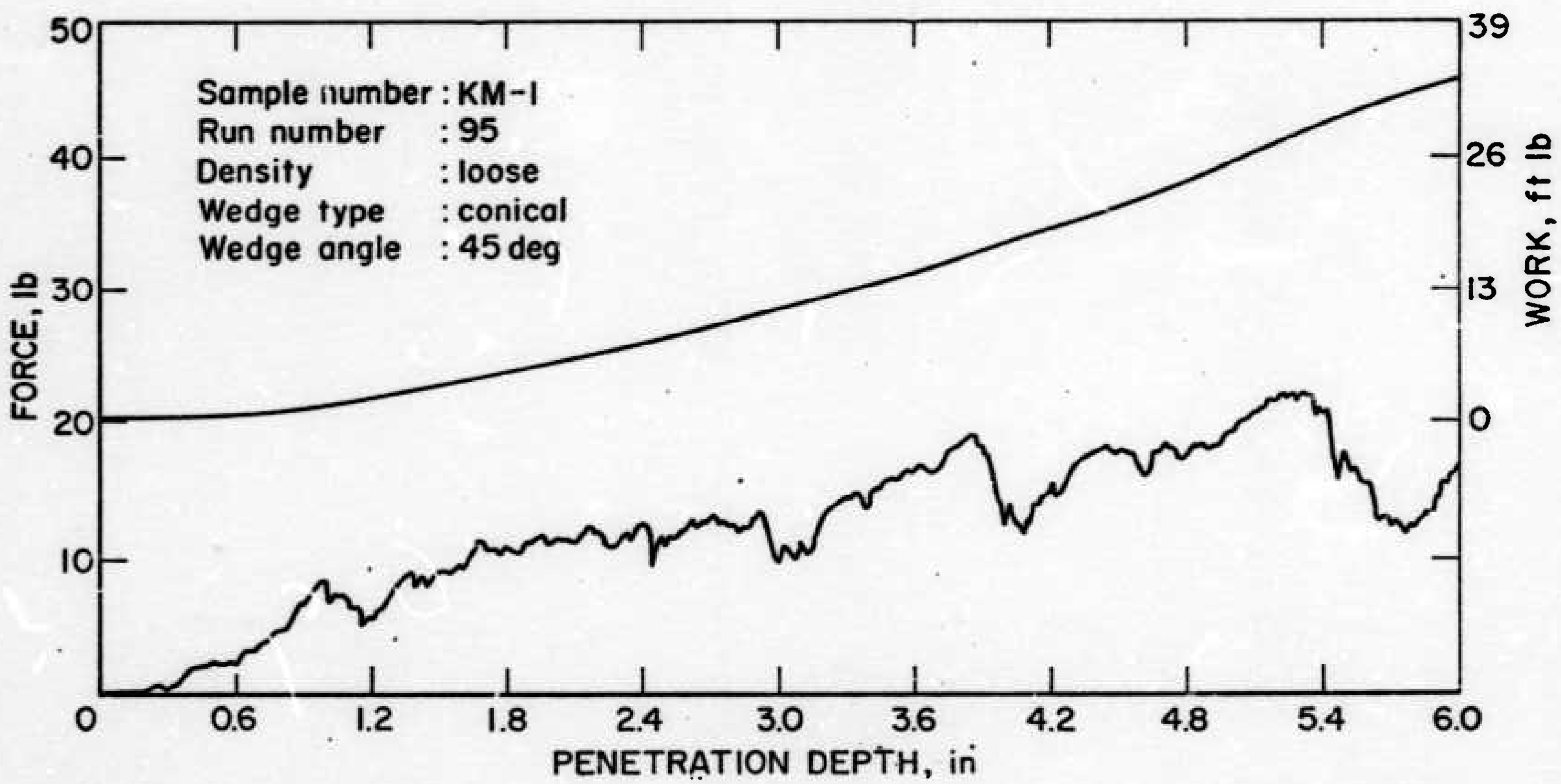
FIGURE 13. - Penetration Test Experimental Data of NAST-3.



PGH-73
422

FIGURE 14. - Penetration Test Experimental Data of KM-1.

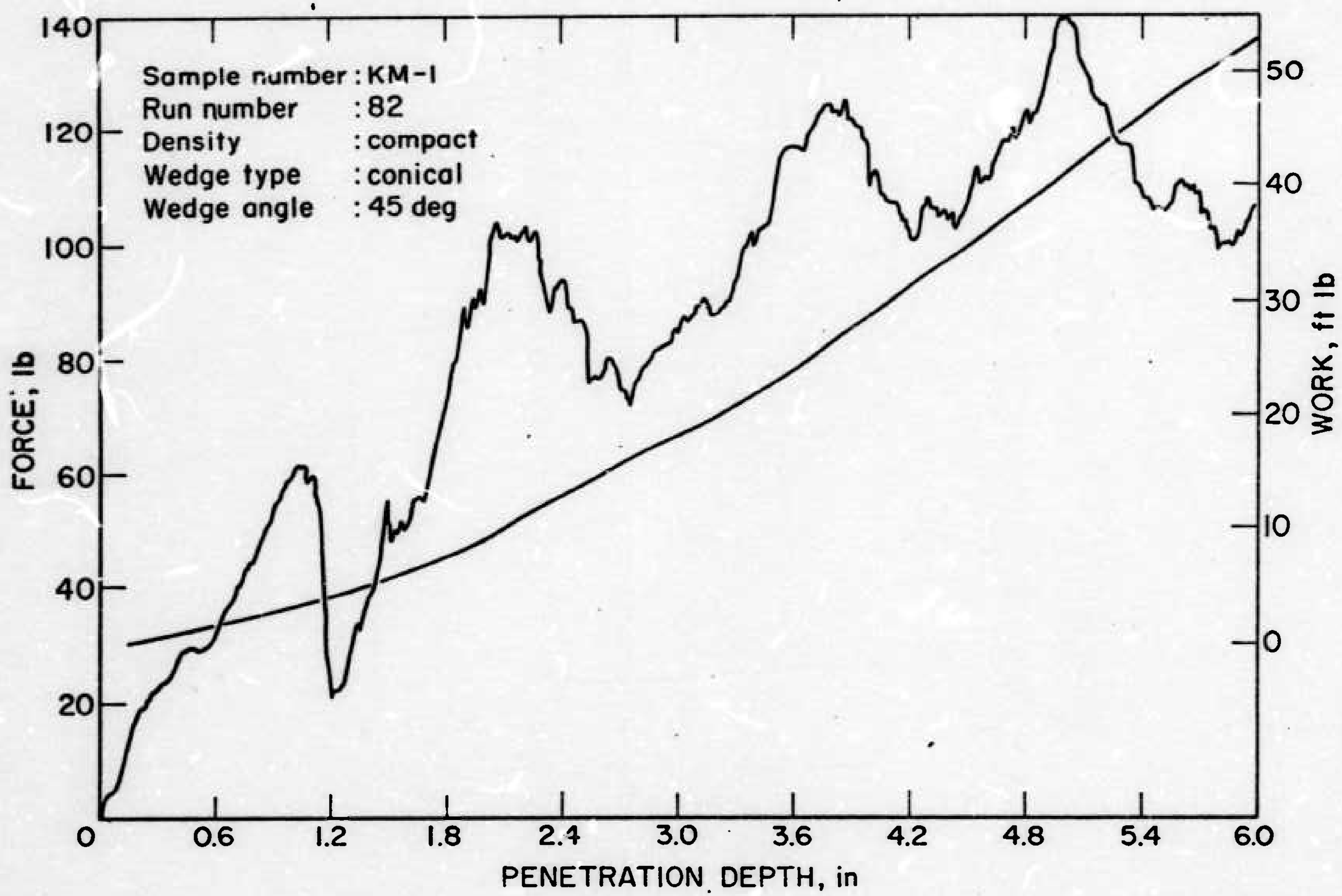


FIGURE 15. - Penetration Test Experimental Data of KM-1.

PGH-73
420

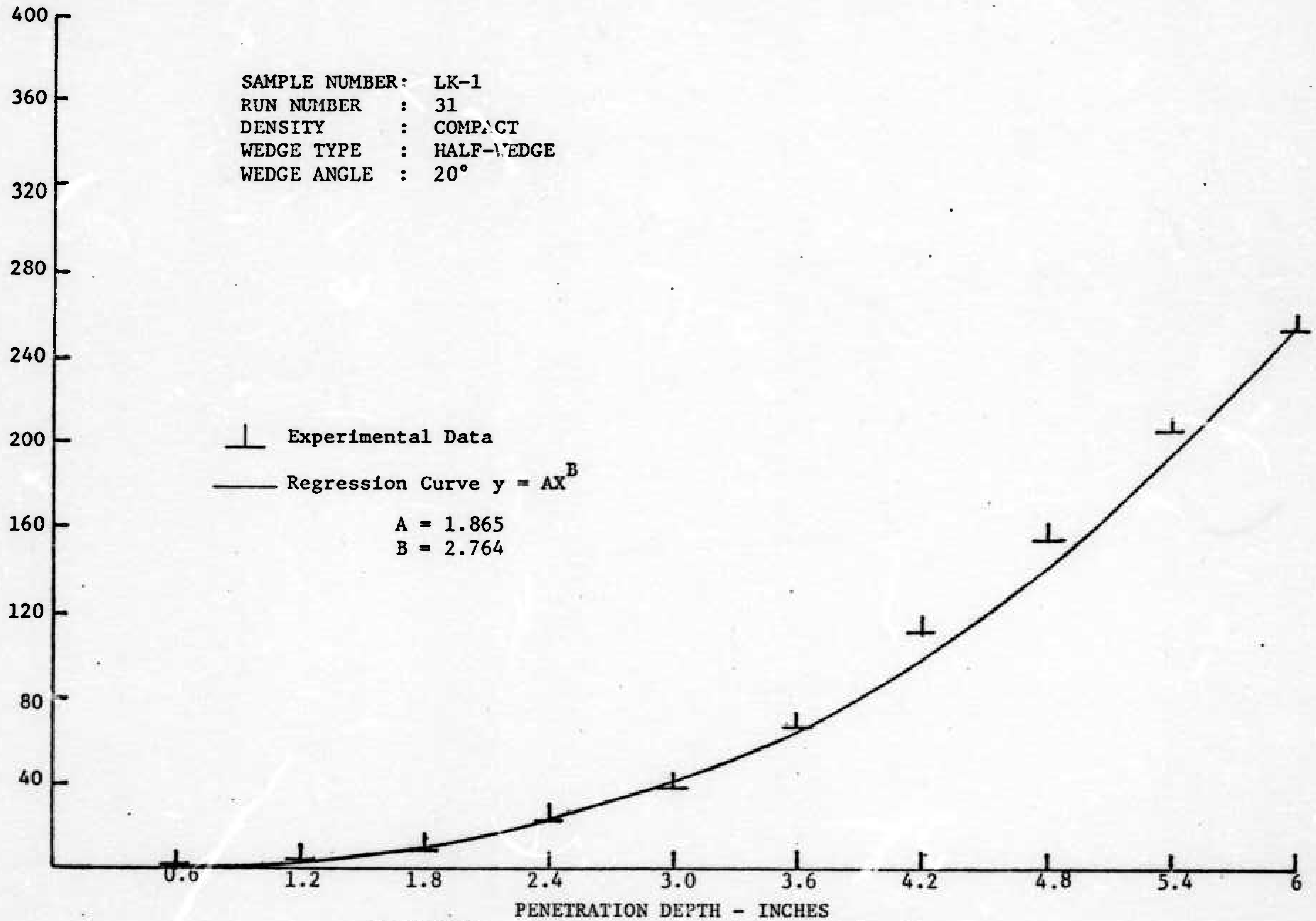


FIGURE 16. - Typical Analytical Penetration Curve.

TABLE 2. - Sample LK-1, loose. Regression analysis of form $Y = AX^B$.

Wedge type	Angle, degree	A	B	Goodness of fit	Y for X = 6
Full	20	0.474	1.988	0.967	16.691
Full	30	1.605	1.774	.978	38.512
Full	45	1.302	1.843	.984	35.377
Half	00	1.030	1.637	.999	19.354
Half	30	0.919	1.393	.972	11.153
Half	45	.632	2.294	.991	38.555
Circular ..	20	.853	1.842	.996	23.139
Circular ..	30	.755	1.916	.993	23.379
Circular ..	45	1.708	1.880	.981	49.588
Conical ...	15	.417	1.424	.929	5.349
Conical ...	20	.202	2.065	.926	8.190
Conical ...	30	.312	1.624	.926	5.732
Conical ...	45	.575	1.751	.964	13.252

TABLE 3. - Sample LK-1, compact. Regression analysis of form $Y = AX^B$.

Wedge type	Angle, degree	A	B	Goodness of fit	Y for X = 6
Full	20	2.069	2.580	.977	210.489
Full	30	0.914	3.068	.989	223.209
Full	45	1.899	2.352	.984	128.345
Half	00	1.865	2.764	.992	264.035
Half	30	1.156	2.316	.944	73.307
Half	45	1.063	2.092	.938	45.145
Circular ..	20	2.547	2.031	.963	96.897
Circular ..	30	1.939	2.428	.986	150.312
Circular ..	45	2.364	2.580	.980	240.577
Conical ...	15	1.171	2.266	.979	67.911
Conical ...	20	.916	2.494	.955	79.992
Conical ...	30	1.307	2.304	.962	81.155
Conical ...	45	1.615	2.221	.981	86.466

TABLE 4. - Sample LK-2, loose. Regression analysis of form $Y = AX^B$.

Wedge type	Angle, degree	A	B	Goodness of fit	Y for X = 6
Full	20	0.31	2.11	.96	13.64
Full	30	.45	1.58	.96	7.72
Full	45	1.13	2.02	.93	42.43
Half	20	.40	1.53	.96	6.27
Half	30	.13	1.74	.84	2.89
Half	45	.48	1.94	.98	15.49
Circular ..	20	.33	1.70	.92	7.03
Circular ..	30	.64	1.52	.98	9.87
Circular ..	45	.31	2.09	.96	12.93
Conical ...	15	.42	1.12	.93	3.15
Conical ...	20	.44	1.37	.95	5.11
Conical ...	30	.57	1.05	.95	3.71
Conical ...	45	.33	1.56	.94	5.32

TABLE 5. - Sample LK-2, compact. Regression analysis of form $Y = AX^B$.

Wedge type	Angle, degree	A	B	Goodness of fit	Y for X = 6
Full	20	0.39	2.66	.94	46.27
Full	30	2.15	2.48	.98	183.33
Full	45	.58	2.79	.99	85.48
Half	20	1.03	2.05	.92	41.00
Half	30	1.28	2.17	.98	62.17
Half	45	.37	2.44	.94	29.58
Circular ..	20	.60	2.65	.98	69.21
Circular ..	30	1.40	2.12	.98	60.40
Circular ..	45	.57	2.46	.97	47.17
Conical ...	15	.78	1.86	.92	21.68
Conical ...	20	.35	2.57	.91	35.12
Conical ...	30	.62	1.83	.92	16.43
Conical ...	45	.65	2.25	.99	36.66

TABLE 6. - Sample NAST-3, loose. Regression analysis of form $Y = AX^B$.

Wedge type	Angle, degree	A	B	Goodness of fit	Y for X = 6
Full	20	0.49	1.72	0.98	10.74
Full	30	.34	1.73	.96	7.43
Full	45	.95	1.83	1.00	25.20
Half	20	.62	1.30	.95	6.30
Half	30	.42	1.57	.96	7.07
Half	45	.44	1.47	.96	6.23
Circular ..	20	.47	1.59	.94	8.14
Circular ..	30	.57	1.15	.78	4.49
Circular ..	45	.62	1.85	.99	17.21
Conical ...	15	.56	.58	.43	1.59
Conical ...	20	.15	1.63	.87	2.83
Conical ...	30	.52	.86	.68	2.45
Conical ...	45	.21	1.96	.93	7.14

TABLE 7. - Sample NAST-3, compact. Regression analysis of form $Y = AX^B$.

Wedge type	Angle, degree	A	B	Goodness of fit	Y for X = 6
Full	20	0.73	1.78	0.90	17.79
Full	30	.43	2.44	.99	34.31
Full	45	.29	2.26	.95	16.83
Half	20	.66	1.55	.98	10.67
Half	30	.32	2.35	.87	21.35
Half	45	1.40	1.58	.99	23.54
Circular ..	20	0.68	2.14	.98	31.08
Circular ..	30	1.03	1.68	.95	20.80
Circular ..	45	.15	1.13	.69	1.17
Conical ...	15	1.55	.39	.83	3.09
Conical ...	20	1.92	.41	.75	4.01
Conical ...	30	1.89	.36	.82	3.60
Conical ...	45	1.95	.43	.81	4.21

TABLE 10. - Work (foot-pounds) for penetration of 6 inches into granular samples.

Sample:		LK-1		LK-2		NAST-3		KM-1	
Sample density:		Loose	Compact	Loose	Compact	Loose	Compact	Loose	Compact
Wedge type	Angle, degree								
Full	20	16.69	210.49	13.64	46.27	10.74	17.79	26.09	32.37
Full	30	38.51	223.21	7.72	183.33	7.43	110.40	30.73	44.22
Full	45	35.38	128.38	42.43	85.48	27.17	16.83	35.99	57.11
Half	20	19.35	264.04	6.27	41.00	6.30	10.67	28.55	23.26
Half	30	11.15	73.31	2.89	62.17	7.07	21.35	21.66	38.29
Half	45	38.56	45.15	15.49	29.58	6.23	23.54	18.63	38.91
Circular .	20	23.14	96.90	7.03	69.21	8.14	31.08	19.06	20.69
Circular .	30	22.38	150.31	9.87	62.40	4.49	20.80	33.67	34.64
Circular .	45	45.59	240.58	12.93	47.17	17.21	1.17	18.12	18.23
Conical ..	15	5.35	67.91	3.15	21.63	1.59	3.09	7.96	2.73
Conical ..	20	8.19	79.99	5.11	35.12	2.83	4.01	11.69	12.24
Conical ..	30	5.73	81.16	3.71	16.43	2.45	3.60	7.79	12.67
Conical ..	45	13.25	86.47	5.32	36.66	7.14	4.21	13.01	36.54

TABLE 11. - Analysis of variance for samples.

Source	Sum of squares	Degrees of freedom	Mean square	Variance ratio
Wedge angle	33,300.21	12	2,775.02	3.69
Material	61,314.47	3	20,438.16	27.20
Compaction	51,835.65	1	51,835.65	69.00
Interactions				
Angle - compaction	18,379.34	12	1,531.61	2.03
Angle - material	28,775.88	36	799.32	1.06
Material - compaction	45,738.61	3	15,246.00	20.29
Angle-Material-Compaction	27,044.31	36	751.23	

These results show that the compaction state (loose or compact) is highly significant at a 95 percent level, as is the sample type. The wedge type and angle are slightly significant at a 95 percent level. In addition, the data indicate that a strong interaction between the material type and compaction state also exists, with little significance for the other interactions.

RECOMMENDATIONS FOR FUTURE RESEARCH

The data analysis should be continued because of the potential contribution to being able to measure the "diggability" of granular materials. In particular, regression analysis and analysis of variance should be completed for the penetration data for the remainder of the test samples. Since the material type was shown to be significant in influencing the work of penetration, the physical property data should be analyzed in detail in conjunction with the penetration data to determine which characteristics of the material cause the observed differences.